OPTICAL PROPERTIES OF WATER ICE BELOW 200 K

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The Galileo mission is leading a new set of detailed investigations of the satellites of the outer planets, whose surfaces (with the exception of the Jovian satellite Io) are composed of mixtures of water ice and minerals and/or carbonaceous compounds. Observations by the Near Infrared Mapping Spectrometer (NIMS) between 0.7 and 5.3 µm in wavelength are able to detect absorption bands of water ice that occur in this spectral region, which are diagnostic of the morphological state (amorphous or crystalline), the mean particle size or sizes, and the temperature of the surface. In theory, one should also be able to accurately estimate the spectral properties of the materials mixed with ice. This, however, is only possible if one has accurate optical constants of water ice in the same crystalline state and having the same temperature as the material observed. Similar spectral images of the infrared solar reflection of icy bodies will be made in the next decade by the Cassini Saturn orbiter and by the Rosetta comet rendezvous mission. I will review the current knowledge of these optical properties at temperatures appropriate to these bodies (60–170 K, for the large and medium satellites of Jupiter and Saturn, and the rings of Saturn).

The most recent description of water ice optical constants in the literature is the review by Warren (1984), which was aimed at the Earth science community, and hence concentrated on measurements made within 30–40 degrees of the freezing point. He made a major adjustment to the 45-µm band due to the lack of any measurements of this region at warmer temperatures. The numbers in this review are only applicable to temperatures near 250 K. It was noted by Warren that the optical properties were quite different at lower temperatures even at wavelengths outside the very sensitive 45-µm lattice absorption. For ice at the temperatures of outer-planet satellites, one must consult other literature.

A complicating factor in this matter is the fact that water condenses in several forms at low pressures, including as many as three distinct types of amorphous ice (Jenniskens and Blake, 1994), a metastable cubic crystalline ice as well as the hexagonal crystalline form which is characteristic of high-temperature ice. The exact morphology or mixture of morphologies of a deposit is not only a function of temperature, but of temperature history. In addition, ice can be amorphized by the interaction with particle radiation (Baratta *et al.*, 1994), which is a common ingredient in the magnetospheric environment of these satellites.

The hexagonal crystalline form is the most stable, and once ice achieves this form, it is retained at any temperature. Ice formed from vapor above about 160 K will be hexagonal, and ice formed at colder temperatures, when heated to 150–160 K or more, will transform to hexagonal crystals on time scales that are shorter at higher temperatures, being nearly instantaneous above 200 K. Around 130–140 K, on vapor deposition or heating, a mixture of cubic and amorphous ice occurs which seems stable (over laboratory time scales) until T>150K. Below 130 K, amorphous ice (the low-density variant in particular, although some of the high-density type may occur below 80 K) is stable (see, e.g., Hobbs, 1975; Bar-Nun *et al.*, 1987; Jenniskens and Blake, 1994). It seems likely, therefore, that there would be a mixture of amorphous and crystalline ice on most of these bodies.

The irreversibility of the crystalline transformation and the apparent lack of significant differences between the spectral properties of cubic and hexagonal ice works in our favor, since several measurements are available of the optical constants of hexagonal ice for T>50 K. Unfortunately, most of these measurements are of thin films, limited to about 100 µm thickness, and thus unable to accurately measure the more transparent region below 2.5 µm. A new set of thick-film measurements has just been completed (Grundy and Schmitt, 1996), however, which provide a high temperature resolution series of absorption measurements from 1–2.5 µm. Beyond 2.5 µm, the data are more sparse, but include, among others, measurements at three temperatures by Tsujimoto *et al.* (1984), at 100 K by Bertie *et al.* (1969), at 163 K by Toon *et al.* (1994), and for the 3 µm band at 150K by Bergren *et al.* (1978). There are many thin-film measurements of amorphous ice samples below 150 K, but no measurements of the important region <2.5 µm, although frost reflectance measurements imply that the optical constants of amorphous ice in this region differ considerably from crystalline ice at the same temperature. Representative measurements of the optical constants of amorphous ice are found in Hudgins *et al.* (1993).

The figures illustrate how the optical properties of ice differ with morphology and temperature and how this effects modeled spectra as compared to measured spectra. I will also present a detailed description of how we use radiative-transfer models to analyze the observations of icy bodies such as those made by NIMS.

REFERENCES

Baratta, G. A. *et al.*, *Planet. Space Sci.*, *42*, 759–766, 1994.

Bar-Nun, A. *et al.*, *Phys. Rev. B*, *35*, 2427–2435, 1987.

Bergren, M. S. *et al.*, *J. Chem. Phys.*, *69*, 3477–3482, 1978.

Bertie, J. E., H. J. Labbe, and E. Whalley, *J. Chem. Phys.*, *50*, 4501–4520, 1969.

Gosse, S., D. Labrie, and P. Chylek, *Appl. Optics*, *34*, 6582–6586, 1995.

Grundy, W. M., and B. Schmitt, *Bull. Am. Astron. Soc.*, *28*, 1071, 1996 (abstract).

Hudgins, D. M. *et al.*, *Astrophys. J. Supp.*, *86*, 713–870, 1993.

Hobbs, P. V., *Ice Physics*, University Press, Oxford, 1974.

Jenniskens, P., and D. F. Blake, *Science.*, *265*, 753–756, 1994.

Kou, L., D. Labrie, and P. Chylek, *Appl. Optics*, *32*, 3531–3540, 1993.

Toon, O. B. *et al.*, *J. Geophys. Res.*, *99*, 25,631–25,654, 1994.

Tsujimoto, S., A. Konishi, and T. Kunitomo, *Cryogenics*, *22*, 603–607, 1982.

Warren, S. G., *Appl. Optics*, *23*, 1206–1225, 1984.

OPTICAL PROPERTIES OF WATER ICE: G. B. Hansen

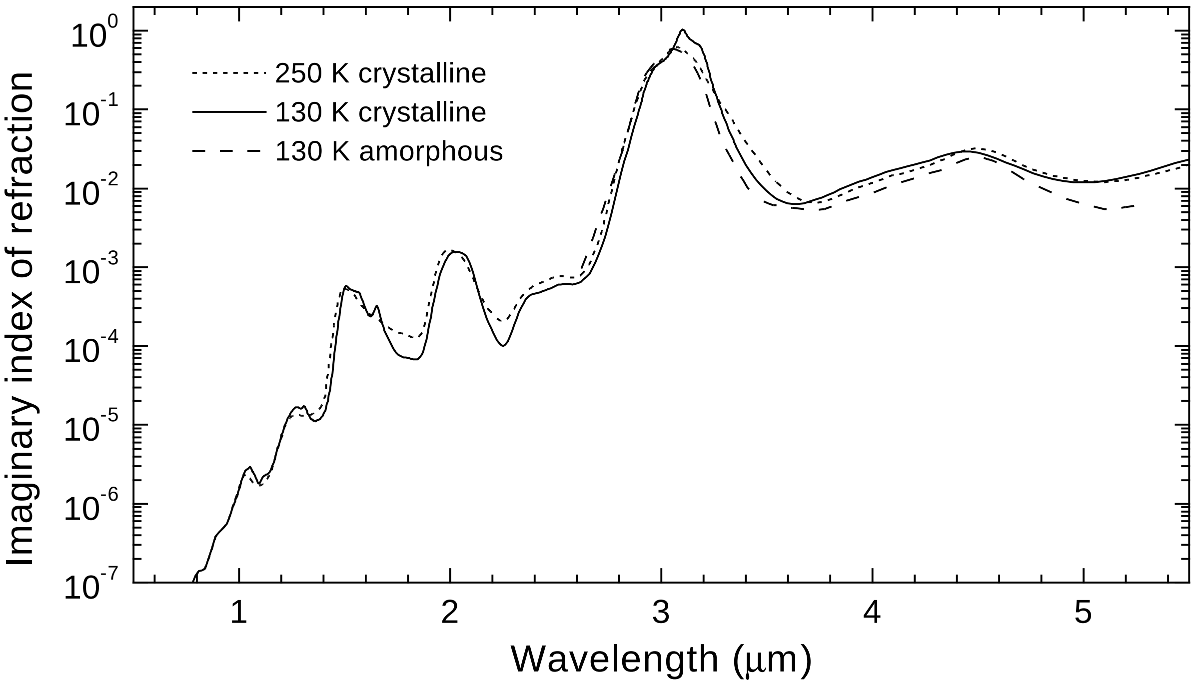

Figure1. The imaginary index of refraction of crystalline water ice at two temperatures and an abbreviated spectrum of 130 K amorphous ice. Note the small shifts in wavelength and significant shape differences of the 1.5- and 2.0-µm bands as the temperature changes from 250 K down to 130 K. The 130 K crystalline ice also has a much different 3.1-µm OH-stretch band shape compared to the other two, and all three differ in the region from 3 to 5.5 µm. The data of Gosse *et al.* (1995) and Kou *et al.* (1993) were used to update the Warren (1984) data for 250 K.

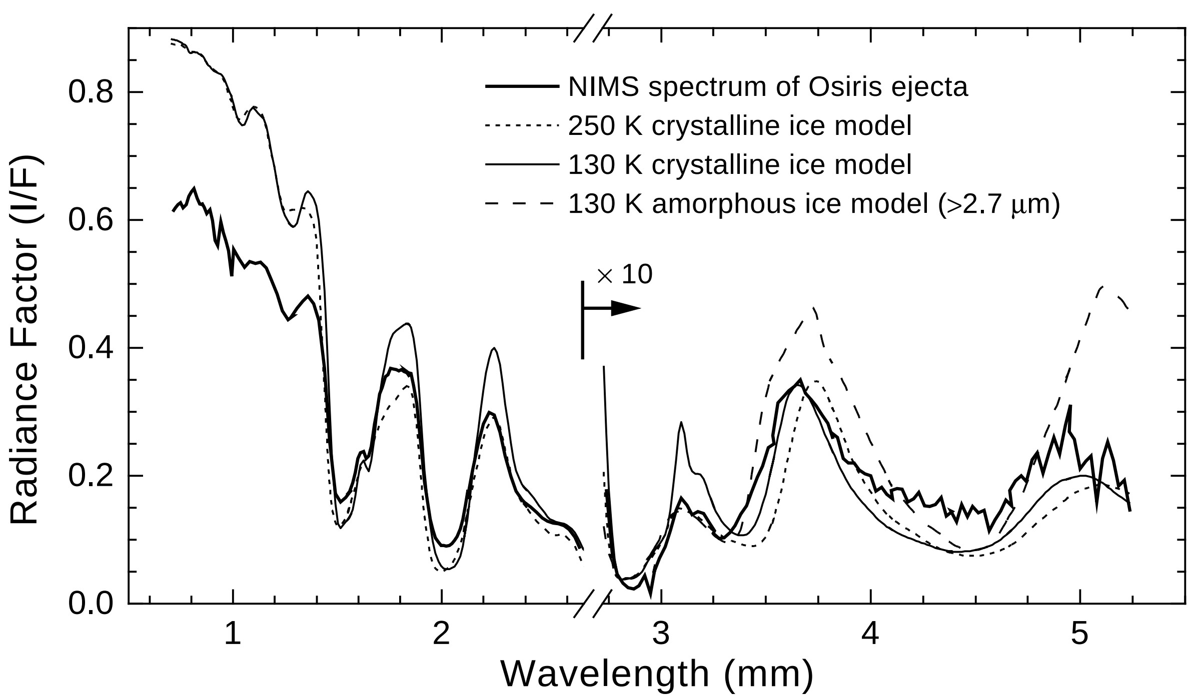

Figure 2. Radiative transfer models of the reflectance of a pure snow deposit with a particle radius of 20 µm using all three optical constants depicted in Fig. 1, along with a NIMS spectrum of an area on Ganymede which resembles the spectrum of pure snow the most. Note how using different optical constants might lead to different conclusions in the interpretetion of the measurements.